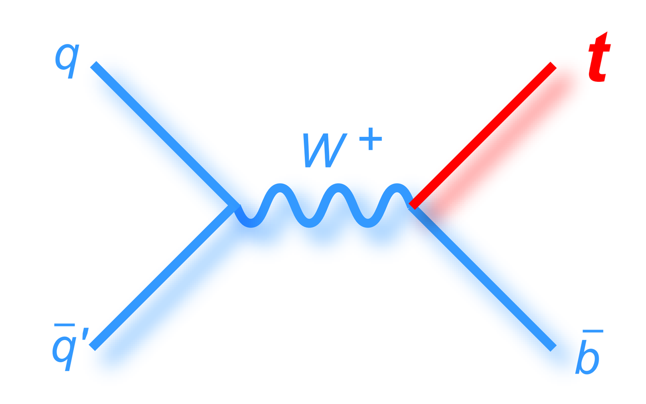
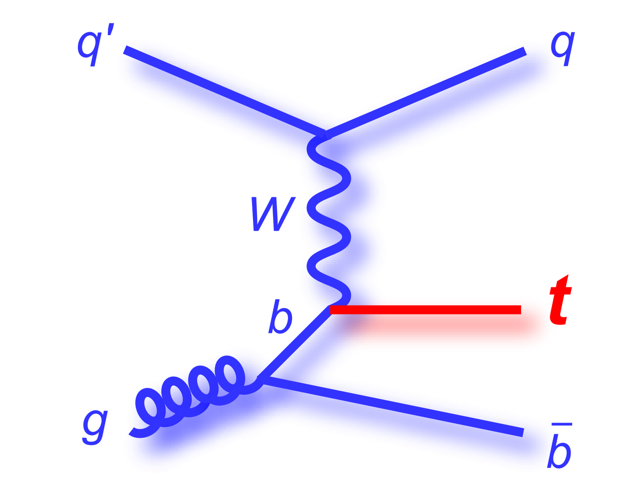


s-channel "*tb*"

Observation of Single Top Quark Production

The DØ Collaboration

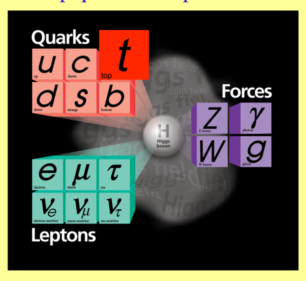
March 2009



t-channel "*tqb*"

Motivation

The top quark is a spin=1/2 fermion with charge +2/3*e*. It is the weak isospin partner of the bottom quark, ~40 × heavier than its partner. It is the heaviest known fundamental particle, with m_{top} = 173.1 ± 1.1 GeV. The top quark is produced mostly in top-antitop pairs at the Tevatron with cross section 7.9 pb. Top quarks are also predicted to be produced singly via the electroweak interaction. By "single" we mean that each top quark is not produced with its antiparticle partner, but instead with a bottom quark and sometimes also a light quark. The top quark decays into a *W* boson and a bottom quark almost 100% of the time.

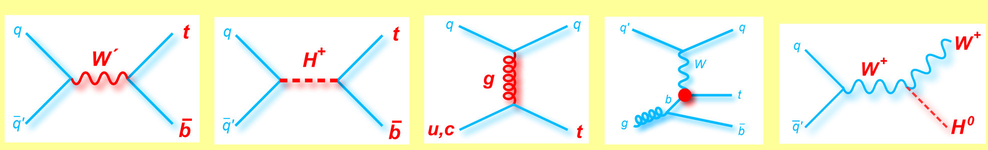


Many aspects of the Standard Model of particle physics can be tested using single top quark production:

Study the *Wtb* coupling in top quark production: measure the CKM quark mixing matrix element $|V_{tb}|$, test CKM unitarity, search for anomalous components in the *Wtb* coupling.

Cross section is sensitive to new physics: s-channel resonances – *W′*, H^+, Kaluza Klein excited W_{KK}, technipion; t-channel – flavor-changing neutral currents (*t-Z/γ/g-u/c*); fourth quark generation.

Higgs boson production (*WH*). Single top quark observation is a step towards the Higgs boson discovery.



Summary

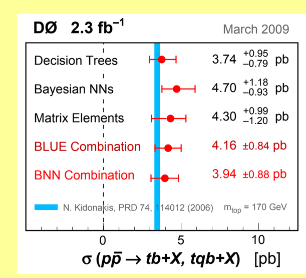
On March 4, 2009, the DØ Collaboration submitted a paper to Physical Review Letters announcing the first observation of single top quark production (arXiv.org:0903.0850). We report the result here.

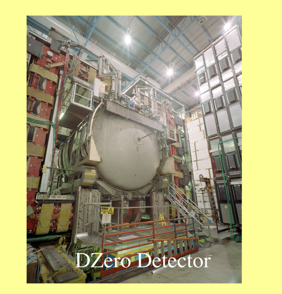
We present the results of a search for single top quark production in 2.3 fb^{-1} of data at the Fermilab Tevatron proton-antiproton collider at 1.96 TeV center-of-mass energy. The predicted cross section for this process is 3.46 ± 1.8 pb for a top quark mass of 170 GeV. Our measurement is:

$$\sigma(pp \to tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$$

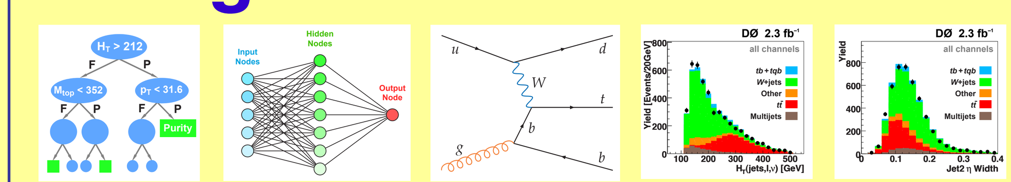
where "*tb*" stands for $t\bar{b} + \bar{t}b$ production, and "*tq*" stands for $tq\bar{b} + \bar{t}\bar{q}b$ production. The probability to measure a cross section at this value or higher in the absence of signal is 2.5×10^{-7}, corresponding to a 5.03 standard deviation significance for the presence of signal. This is considered an unlikely enough occurrence (1 in 4 million) that our measurement meets the standard to be called an observation of a new physics process. The results of our analysis are illustrated in the plot below.

Fermilab Tevatron Collider





Signal Discrimination



We apply three multivariate methods to separate signal from background:

Boosted Decision Trees. A decision tree applies sequential cuts to the events but does not reject events that fail the cuts. Boosting averages the results over many trees and improves the performance by about 20%.

Best Variables to Separate Single Top from W+Jets
DØ 2.3 fb^{-1} Analysis

Object kinematics	$\not{E}_T$
	p_T(jet2)
	p_T^{rel}(jet1,tag-μ)
	E(light1)
Event kinematics	*M*(jet1,jet2)
	M_T(W)
	H_T(lepton,$\not{E}_T$,jet1,jet2)
	H_T(jet1,jet2)
	H_T(lepton,$\not{E}_T$)
Jet reconstruction	Width_ϕ(jet2)
	Width_η(jet2)
Top quark reconstruction	M_{top}(*W*,tag1)
	ΔM_{top}^{min}
	M_{top}(*W*,tag1,S2)
Angular correlations	cos(light1,lepton)$_{\text{btaggedtop}}$
	Δφ(lepton,$\not{E}_T$)
	Q(lepton) x η(light1)

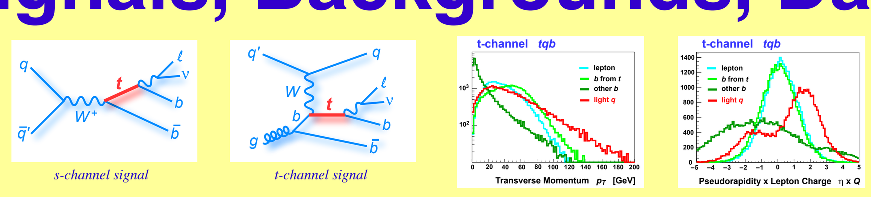
Bayesian Neural Networks. A neural network is trained on signal and background samples to obtain weights between the network nodes. Bayesian NNs average over a large number of networks to improve the performance.

Matrix elements. This method was pioneered by DØ in the top quark mass measurement in a 2004 *Nature* paper. It uses the 4-vectors of the lepton and jets and the Feynman diagrams to compute an event probability density for the signal and background hypotheses.

Best Variables to Separate Single Top from Top Pairs
DØ 2.3 fb^{-1} Analysis

Object kinematics	*pT*(notbest2)
	pT(jet4)
	pT(light2)
Event kinematics	*M*(alljets–tag1)
	Centrality(alljets)
	M(alljets–best1)
	H_T(alljets–tag1)
	H_T(lepton,$\not{E}_T$,alljets)
	M(alljets)
Jet reconstruction	Width_η(jet4)
	Width_ϕ(jet4)
	Width_ϕ(jet2)
Angular correlations	cos(lepton$_{\text{btaggedtop}}$, btaggedtop$_{\text{CMframe}}$)
	Q(lepton) x η(light1)
	Δ*R*(jet1,jet2)

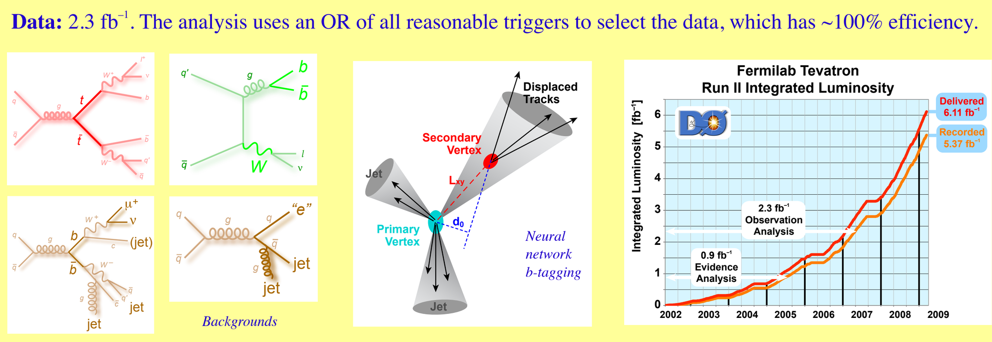
Signals, Backgrounds, Data



Single top signature: one isolated high transverse momentum lepton (electron or muon), and missing transverse energy, which combined indicate the decay of a *W* boson (from the top quark decay), and two, three, or four jets. One or two of the jets must be identified as coming from a *b* decay ("tagged"). The jets may be in any part of the calorimeter (not just the central region), see the kinematics of the t-channel signal in the plot above.

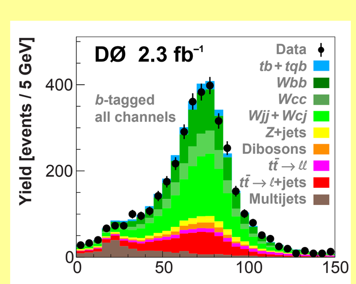
Backgrounds: *W*+jets events, top pairs, multijets, and smaller contributions from *Z*+jets and dibosons.

Data: 2.3 fb^{-1}. The analysis uses an OR of all reasonable triggers to select the data, which has ~100% efficiency.



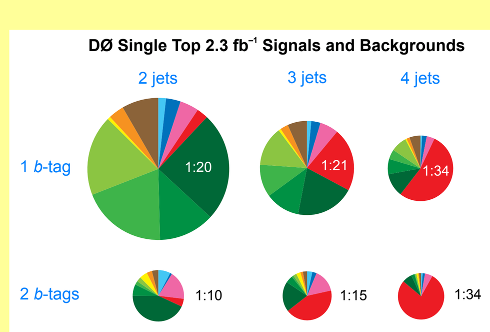
Event Yields

Before *b*-tagging, we have 114,777 data events, with a predicted signal content of 444 events (s-channel + t-channel combined). This is a signal:background ratio of 1:258. We improve this by selecting events with one tight *b*-tag or two loose *b*-tags, to obtain an average S:B of 1:20. The signal acceptance is (2.9 ± 0.3)% of the total production cross section. We perform the analysis in 24 separate channels (electron, muon; 2, 3, 4 jets, 2 *b*-tags; Run IIa, Run IIb), plots are shown here with all channels combined for illustration only.

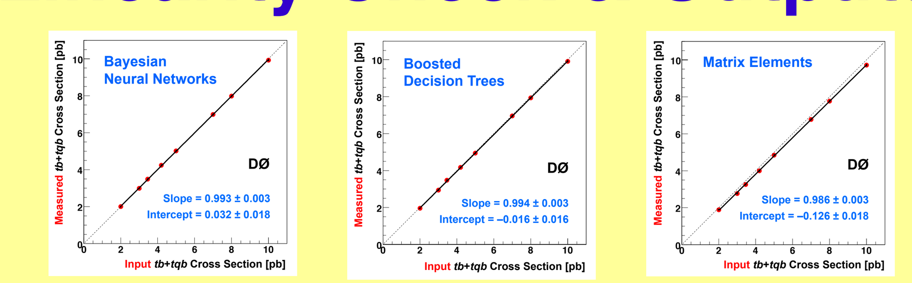


Event Yields in 2.3 fb^{-1} of DØ Data
Electron + muon, 1 tag + 2 tags combined

Source	2 jets	3 jets	4 jets
s-channel *tb*	62 ± 9	24 ± 4	7 ± 2
t-channel *tqb*	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
W+cj	435 ± 27	113 ± 7	24 ± 2
W+jj	413 ± 26	140 ± 9	41 ± 3
Z+jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \to \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \to \ell$+jets	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	2,615 ± 192	1,294 ± 107	742 ± 80
Data	2,579	1,216	724

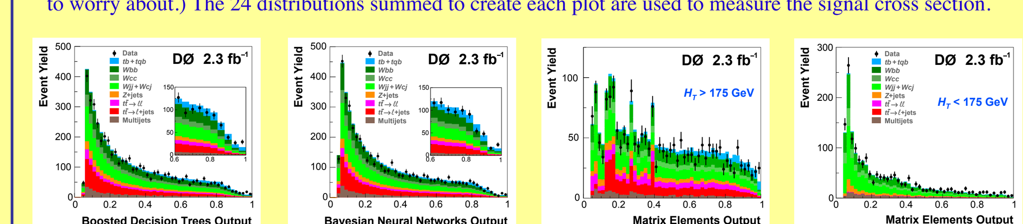


Linearity Check & Outputs



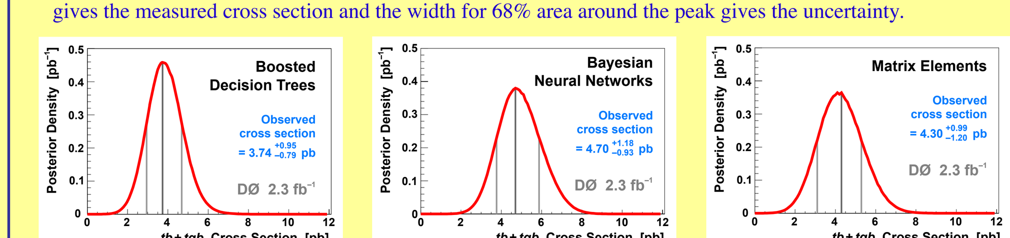
We use ensembles of pseudo-datasets to test the performance of the discriminants – do they accurately measure the signal cross section? The three plots above show that indeed they do.

The four plots below show the outputs from each analysis, for all channels combined. (The spikes in the high-H_T matrix elements plot are a result of summing many channels for the plot with different statistics and are nothing to worry about.) The 24 distributions summed to create each plot are used to measure the signal cross section.

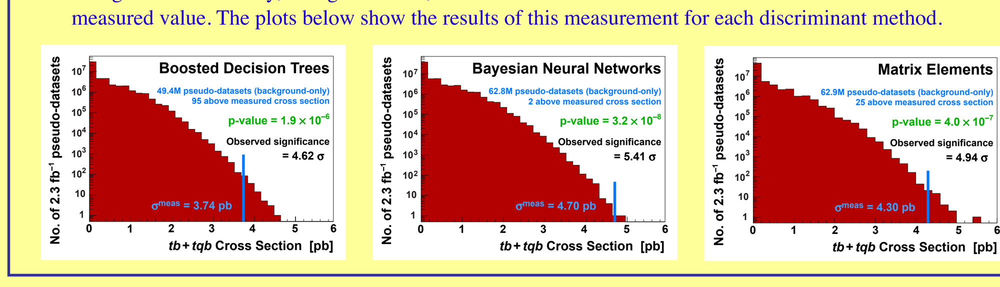


Separate Results

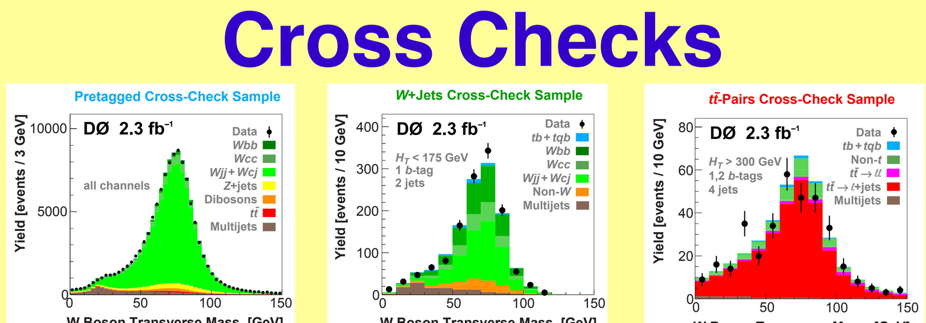
We use the discriminant output distributions from each analysis channel together with the normalization and shape systematic uncertainties to do a Bayesian binned likelihood calculation. We assume a flat non-negative prior for the signal cross section; the posterior density distributions are shown below. The position of the peak gives the measured cross section and the width for 68% area around the peak gives the uncertainty.



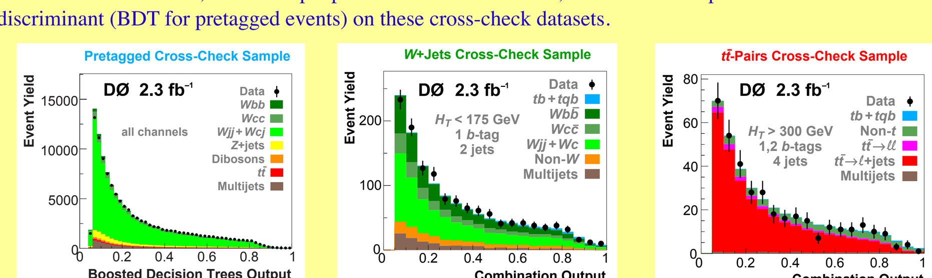
To determine the significance of the signal, we use a very large ensemble of pseudo-datasets containing background events only, no signal events, and measure how often the cross section fluctuates above the measured value. The plots below show the results of this measurement for each discriminant method.



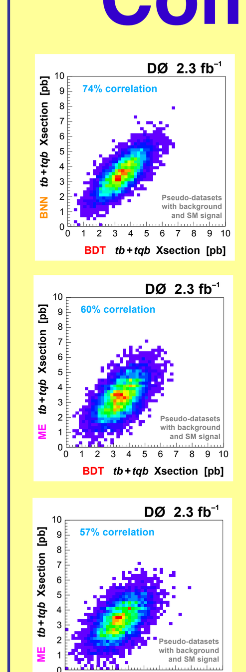
Cross Checks



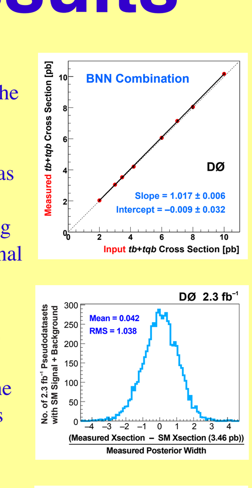
We check the distributions of about 160 variables in every analysis channel before and after *b*-tagging to confirm good data-background agreement. We define two cross-check datasets that contain mostly *W*+jets events and mostly top quark pairs, so that we can independently test their shapes and normalizations. Satisfactory agreement is found in all variables, with example plots shown above. Below, we show the output from the final combination discriminant (BDT for pretagged events) on these cross-check datasets.

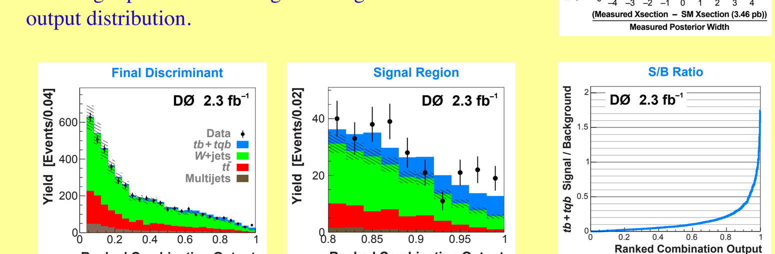


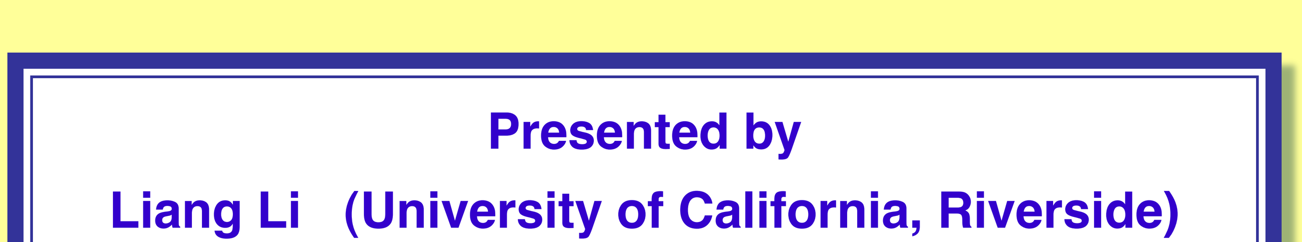
Combination of Results



To improve the expected significance (and hopefully the observed significance) of the measurement, we combine the output distributions from the three discriminant methods, since they are not 100% correlated (see plots to the left). We do this by using the discriminant output distributions as inputs to a Bayesian neural network trained to do the combination. We test the linearity of the BNN output using ensembles of pseudo-datasets containing background, signal at different cross sections, and all uncertainties, shown in the upper right plot. The plot on the right shows the pull distribution for the SM-signal pseudo-datasets. Both plots show excellent performance. The plots below show the results of the combination: the discriminant output; and the lower right plot shows the signal/background ratio for this output distribution.







Systematic Uncertainties

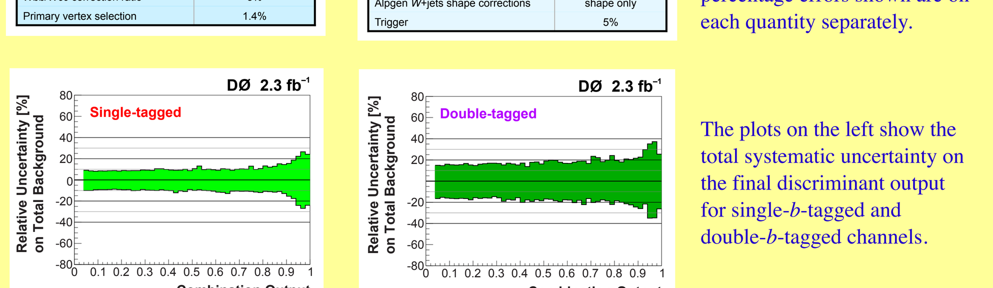
Systematic Uncertainties
Ranked from Largest to Smallest Effect on Single Top Cross Section
DØ 2.3 fb^{-1}

Larger terms	
b-ID tag-rate functions (includes shape variations)	(2.1–7.0)% (1-tag) (9.0–11.4)% (2-tags)
Jet energy scale (includes shape variations)	(1.1–13.1)% (signal) (0.1–2.1)% (bkgd)
W+jets heavy-flavor correction	13.7%
Integrated luminosity	6.1%
Jet energy resolution	4.0%
Initial- and final-state radiation	(0.6–12.6)%
b-jet fragmentation	2.0%
$t\bar{t}$ pairs theory cross section	12.7%
Lepton identification	2.5%
Wbb/*Wcc* correction ratio	5%
Primary vertex selection	1.4%

Systematic Uncertainties
Ranked from Largest to Smallest Effect on Single Top Cross Section
DØ 2.3 fb^{-1}

Smaller terms	
Monte Carlo statistics	(0.5–16.0)%
Jet fragmentation	(0.7–4.0)%
Branching fractions	1.5%
Z+jets heavy-flavor correction	13.7%
Jet reconstruction and identification	1.0%
Instantaneous luminosity correction	1.0%
Parton distribution functions (signal)	3.0%
Z+jets theory cross sections	5.8%
W+jets and multijets normalization to data	(1.8–3.9)% (*W*+jets) (30–54)% (multijets)
Diboson theory cross sections	5.8%
Alpgen *W*+jets shape corrections	shape only
Trigger	5%

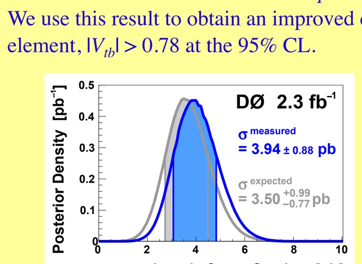
The total uncertainty on our measurement of the single top quark cross section is ±22%. When we calculate this with no systematics included, it is 18% (the statistical uncertainty), so the systematics contribute approximately 13% to the total uncertainty. The components contributing to this are shown in the tables to the left. The percentage errors shown are on each quantity separately.



The plots on the left show the total systematic uncertainty on the final discriminant output for single-*b*-tagged and double-*b*-tagged channels.

Conclusions

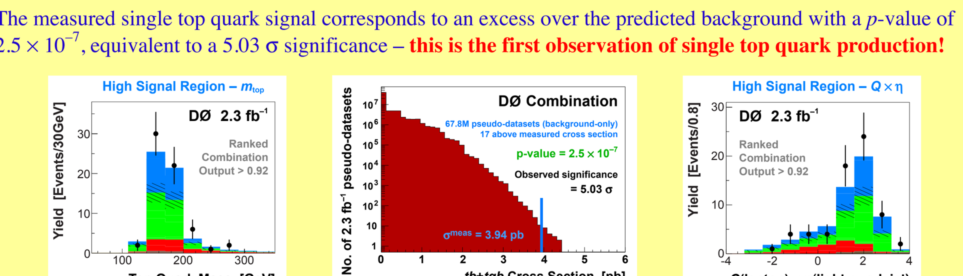
We have measured the single top quark production cross section using 2.3 fb^{-1} of data at the DØ experiment. The cross section for the combined *tb*+*tqb* channels is 3.94 ± 0.88 pb, as shown in the posterior plot and table below. We use this result to obtain an improved direct measurement of the amplitude of the CKM quark mixing matrix element, $|V_{tb}| > 0.78$ at the 95% CL.



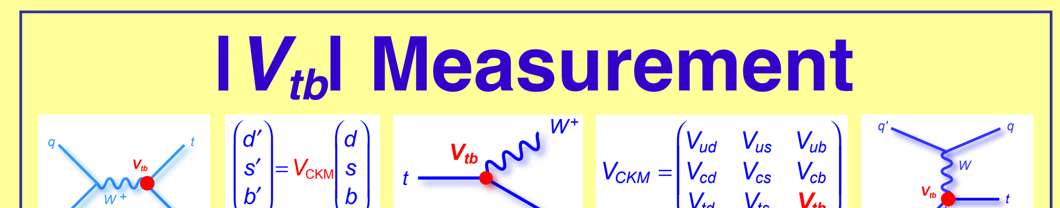
DØ 2.3 fb^{-1} Single Top Results

Analysis Method	Single Top Cross Section	Significance Expected	Significance Measured
Boosted Decision Trees	3.74 $^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	4.70 $^{+1.18}_{-0.93}$ pb	4.1 σ	5.2 σ
Matrix Elements	4.30 $^{+0.99}_{-1.20}$ pb	4.1 σ	4.9 σ
Combination	3.94 ± 0.88 pb	4.5 σ	5.0 σ

The measured single top quark signal corresponds to an excess over the predicted background with a *p*-value of 2.5×10^{-7}, equivalent to a 5.03 σ significance – **this is the first observation of single top quark production!**

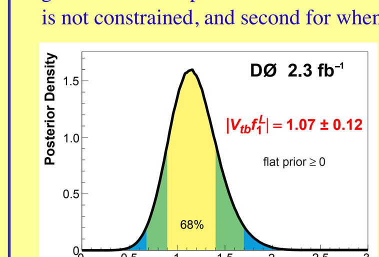


$|V_{tb}|$ Measurement



$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

The Cabibbo-Kobayashi-Maskawa matrix describes the mixing between quarks to get from the strong-interaction eigenstates to the weak-interaction ones (see above). The single top quark production cross section is proportional to $|V_{tb}|^2$ and can thus be used to measure the amplitude of V_{tb}. We assume the standard model for top quark decay and that the *Wtb* coupling is left-handed and *CP*-conserving. We do not assume there are exactly three quark generations. The plots below show our results, first for when the strength of the left-handed scalar coupling f_1^L is not constrained, and second for when it is set equal to one.



Additional Systematic Uncertainties for the $|V_{tb}|$ Measurement
DØ 2.3 fb^{-1}

For the *tb*+*tqb* theory cross section	
Top quark mass	4.2%
Parton distribution functions	3.0%
Factorization scale	2.4%
Strong coupling α_s	0.5%